Single-Layer Broadband Linearly Polarized Reflectarray Antenna by Using Phase-Delay Lines

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Abstract- In this paper, a novel X-band broadband single-layer unit cell with attached phase-delay lines for reflectarray antennas is proposed to surmount the limitation of the reflectarray bandwidth. The unit cell is composed of three circular rings, each with a pair of gaps which are mutually placed orthogonally, and two identical circular phase-delay lines are attached to the outer ring to provide the required reflection phase. After the simulation for the unit cell carried out, a large reflecting phase range of about 600° and almost linear phase curve are achieved at the center frequency of 10 GHz. Parallel phase curves of different frequencies ranging from 9 GHz to 12 GHz are also obtained. To validate the broadband performance of the proposed unit cell, a 9 × 9 center-fed reflectarray antenna operating at X band is designed and simulated. Simulation results show that the designed antenna has 34 % 1-dB gain bandwidth, which demonstrates that an obvious improvement on the bandwidth has been achieved compared to the previous works. Besides, the cross-polarization level is decreased to −40 dB by a mirror symmetric element arrangement.

1. INTRODUCTION

Recently, microstrip reflectarray antennas have attracted wide attentions in many communication and radar applications due to its various advantages [1]. Its low cost, light weight and planar structure make it an alternative high gain antenna to traditional parabolic reflector antenna and phased array antenna. In its basic form, a microstrip reflectarray antenna is composed of an array of radiating elements printed on a flat surface, which are illuminated by a space feed. The main principle of designing a reflectarray antenna is to control the phase of the wave that is reradiated from the radiating elements to form a planar phase front in the desired direction. Several methods have been used as the phase shift mechanism to obtain the desired reflecting phase, such as using element with variable size [2], phase delay line [3], and element rotation [4].

However, there are some drawbacks and limitations for reflectarray antennas, and the most important is narrow bandwidth [5]. The bandwidth of a microstrip reflectarray antenna is mainly restricted by two reasons: first, the narrow bandwidth nature of the microstrip antenna unit cell, and second, the differential spatial phase delays between the feed and elements in the reflectarray. For small and moderate-size microstrip reflectarray antennas, the first factor is more significant to the bandwidth limitation. In order to improve the bandwidth, many techniques have been proposed, such as using elements with phase-delay lines [6], thick substrate, multilayered structure [7], and subwavelength technique [8]. In consideration of low cost and low mass, the single-layer element with phase-delay line technique is more attractive. Many researches have been done to improve the bandwidth of reflectarrays based on this technique [9, 10]. In previous works, circular patches with

two circular phase-delay lines, circular patches with four circular phase-delay lines, and triple circular rings with four quasi-spiral phase-delay lines have been applied to improve the reflectarray bandwidth. However, there are still some potential to enhance the reflectarray bandwidth. For the phase-delay line technique, we have already done some researches [11] and a better bandwidth performance has been achieved compared to the previous works.

Based on our previous work [11], a novel X-band broadband single-layer reflectarray element is proposed to further surmount the limitation of the reflectarray bandwidth, which provides a large reflecting phase range of about 600° and almost linear phase responses at the center frequency of 10 GHz. The unit cell is composed of three circular rings, each with a pair of gaps which are placed orthogonally, and two identical circular phase-delay lines are attached to the outer ring to provide the required reflection phase. Parallel phase curves of different frequencies ranging from 9 GHz to 12 GHz are obtained, which is helpful to achieve broadband characteristics. To validate the broadband performance of the proposed unit cell, a 9 × 9 center-fed reflectarray antenna operating at X band is designed and simulated in a full wave environment. Simulation results show that an obvious improvement on the bandwidth property has been achieved compared to the previous works. Besides, the cross-polarization level is effectively decreased by a mirror symmetric element arrangement [12].

The paper is organized as follows. Section 2 introduces the detailed property and analysis of the proposed unit cell. In Section 3, we present the simulated results of the designed reflectarray antennas to validate the effectiveness. Finally, section 4 presents the conclusion.

2. UNIT CELL DESIGN AND ANALYSIS

The novel reflectarray element, shown in Fig. 1, has been etched on a 0.8-mm-thick dielectric substrate with relative permittivity and loss tangent of 3.55 and 0.0027, respectively. A 2-mm-thick air is utilized here to get more linear phase responses, which separates the dielectric substrate and the metallic ground. As can be seen in Fig. 1, the unit cell is composed of two parts, the inner multi-resonant structure and the outer phase-delay lines. The inner structure consists of three circular rings, each with a pair of gaps, which placed orthogonally. The widths of these three pairs of gaps are g_i, g_m, and g_o for the inner, middle, and outer ring, respectively. And w_i, w_m, and w_o are the widths of these three circular rings, with their corresponding radius of R_i, R_m, and R_o, respectively. Then the outer phase-delay lines are attached to the inner structure through two microstrip stubs. The rotation angle θ represents the length of the phase-delay lines, and the required reflecting phases for each unit cell can be achieved by varying the length of the phase-delay lines. For broadband design, the element

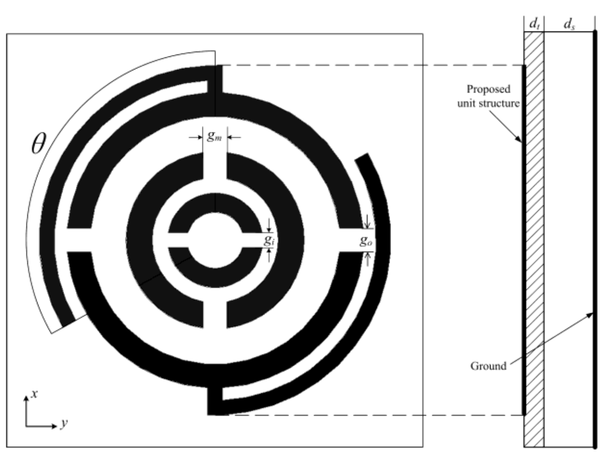


Figure 1. Geometry of the proposed unit cell structure.

spacing is set to be 14 mm, which equals to 0.467 λ at the center frequency of 10 GHz.

The simulation for the unit cell is carried out in HFSS software, in which master-slave boundary condition and floquet port excitation are adopted. The geometry parameters have been optimized to get better performances of the unit cell. Simulated phase response curves versus θ of different frequencies are depicted in Fig. 2. It is observed that, over 600° phase variation is obtained at center frequency of 10 GHz. Besides, the simulated phase curves show a smooth and linear property with smaller slopes. It is worth noting that, the four reflecting phase curves of 9, 10, 11, 12 GHz maintain parallel with each other and the phase deviation between different frequencies is very small, which is quite helpful for achieving broadband performances.

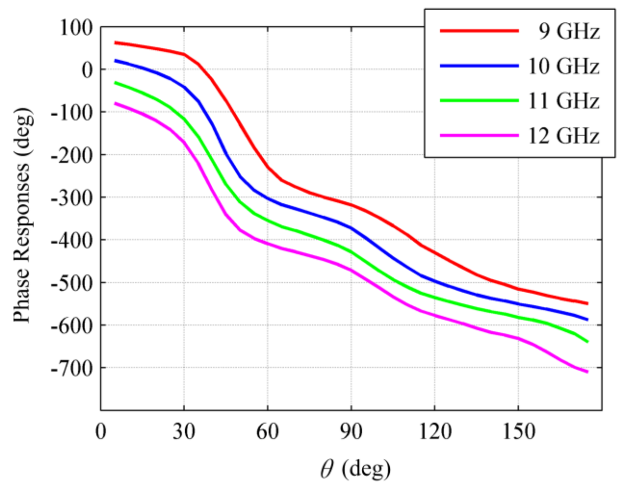
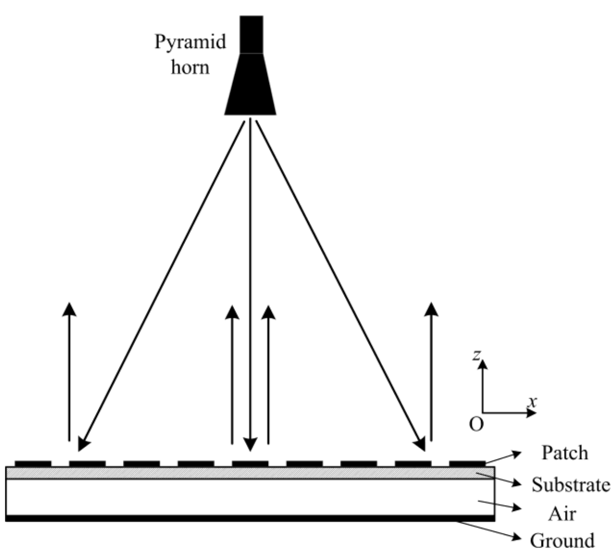


Figure 2. Reflection phase curves versus the lengths of phase-delay lines.

3. REFLECTARRAY DESIGN AND RESULTS

In order to demonstrate the effectiveness of the proposed unit cell, a 9 × 9-element reflectarray antenna is designed and simulated in a full wave environment. A linearly polarized pyramid feed horn is used here to be the space source, which is positioned 82 mm above the reflectarray plane. And the schematic diagram for the



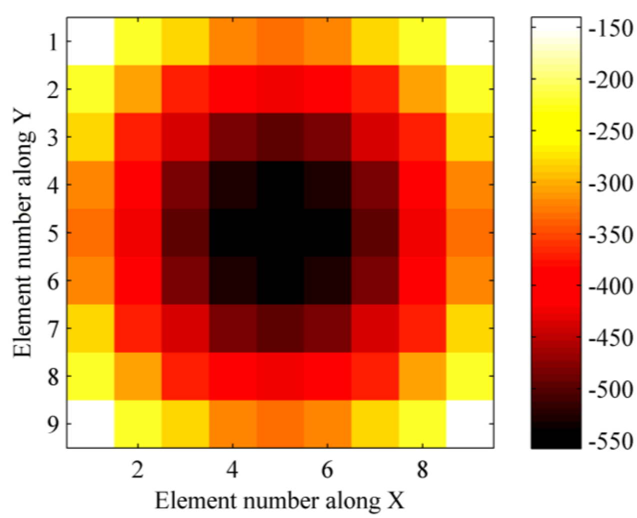


Figure 3. Schematic diagram of the designed reflectarray. Figure 4. Phase distribution on reflectarray aperture.

reflectarray antenna is depicted in Fig. 3.

The required reflecting phases for all the unit cells on the reflectarray aperture can be calculated at the center frequency of 10 GHz, according to (1).

$$\phi_R = k_0 \left(d_i - \left(x_i \cos\varphi_0 + y_i \sin\varphi_0 \right) \sin\theta_0 \right) \tag{1}$$

where k_0 is the propagation constant in free space, d_i is the distance from the feed to the ith unit cell on the reflectarray plane, (θ_0, φ_0) is the designed main beam direction. Here, the phase shifts are calculated for (θ_0, φ_0) = (0°, 0°) at 10 GHz, which means that the main beam is normal to the reflectarray plane. The calculated phase distribution on reflectarray aperture at 10 GHz is shown in Fig. 4. Based on the results shown in Fig. 4, the reflectarray model is built as shown in Fig. 5. It can be seen that the elements are placed in mirror symmetric configuration so as to decrease the cross polarization.

The simulation for the reflectarray antenna has been carried out in a full wave environment by using CST Microwave Studio software and simulated results are presented as follows. The simulated co-polar and cross-polar (X-pol) radiation patterns of E-plane and H-plane at 9 GHz and 10 GHz are shown in Fig. 6 and Fig. 7, respectively. As can be seen, a peak gain at 10 GHz of 20.5 dB has been achieved, which is equivalent to about 50 % efficiency. At the same time, the radiation patterns maintain stable at different frequencies. It can be

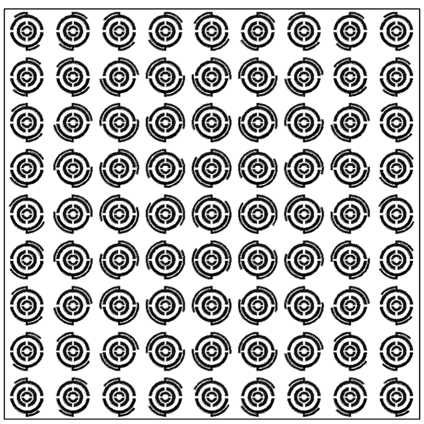


Figure 5. Top view of the reflectarray plane.

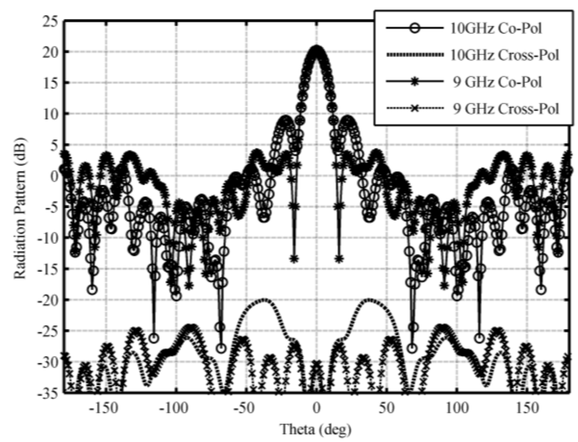


Figure 6. E-plane radiation patterns at 9 GHz, 10 GHz.

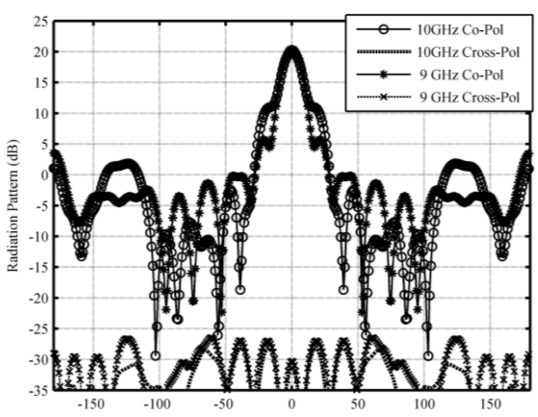


Figure 7. H-plane radiation patterns at 9 GHz, 10 GHz.

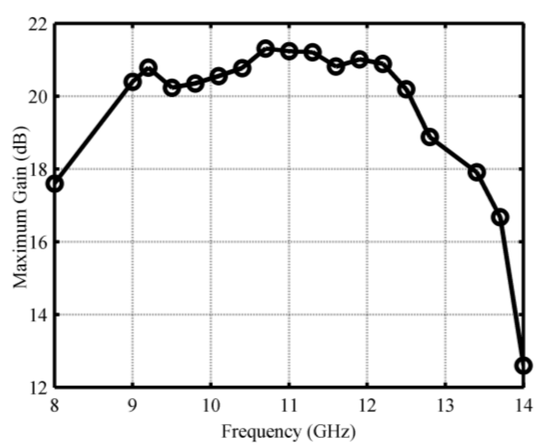


Figure 8. Maximum gain versus frequency.

observed that, the cross polarization levels for both principle planes are reduced below −40 dB, which is an obvious improvement for this kind of reflectarray antennas. Fig. 8 shows the simulated gain against frequency. It is worth noting that 1-dB gain bandwidth is about 34 %, which covers from 9 GHz to 12.4 GHz. An obvious improvement on bandwidth performances is achieved, which can fully demonstrate the effectiveness of the proposed unit cell.

4. CONCLUSION

A novel single-layer unit cell with attached phase-delay lines is proposed for designing broadband reflectarray antennas and linear phase response covering about 600° is achieved. In order to validate the effectiveness of the unit cell, a 9 × 9 center-fed reflectarray operating at X band is then designed and simulated in a full wave environment. The simulation results of 34 % 1-dB gain bandwidth demonstrate an improved bandwidth performance of the designed reflectarray compared with the previous works. In addition, the cross polarization level is decreased below −40 dB.

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